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PRECIPITATION OF ASH PARTICLES ON COOLED
BLADES OF GAS TURBINES

By

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English Pages: 14

Source: Energomashinostroyeniye, No. 8, 1961, pp. 42-45

PREPARED BY:

TRANSLATION SERVICES BRANCH
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

Date 21, Aug. 19 62

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THE EFFECT OF THERMOPHORESIS ON THE PROCESS OF PRECIPITATION

OF ASH PARTICLES ON COOLED BLADES OF GAS TURBINES

S. Sh. Rozenberg, Engineer

Certain ideas are presented concerning the important
influence exerted by the thermophoresis effect on the
process of precipitation of particles on cooled blades
of gas turbines. Experiments on a cooled and an uncooled
plate (a blade model) showed that in comparison with
other factors this phenomenon exerts the most important
influence on the process of precipitation of particles.

Modern gas-turbine construction is characterized by the tendency to increase
the gas temperature in front of the turbine while cooling the most heavily stressed
components of the machine and by the tendency to use inexpensive types of fuel.
However, owing to the presence of ash in the combustion products of heavy liquid
and solid fuels, the use of these fuels causes additional complications resulting
from erosion, corrosion, and precipitation of ash in the flow-through sections of
gas turbines. Practice shows that these difficulties increase in high-temperature
turbines. Thus the study of the process of precipitation on cooled surfaces,
including blades, is of indubitable interest in the field of gas-turbine
construction.

The precipitation of ash on turbine blades is a complex physicochemical
process, in which forces of different origin may play a role, depending on the

conditions of precipitation of the solid particles. These forces may be mechanical hydrodynamic, chemical, molecular, thermal, or electrostatic. One of the causes of precipitation of ash particles and their retention on a surface is the action, of thermophoresis forces. As is known, the thermophoresis effect occurs when aerosol particles suspended in a temperature field move into a region of lower temperatures, i.e., towards a cold body [1].

The thermophoresis force acting on a spherical aerosol particle in the absence of convection currents without taking into account radiative heat transfer from the particle can be calculated from the formula given in Ref. [1]:

$$F_t = -9\pi \frac{\lambda_a}{2\lambda_a + \lambda_i} \; \frac{\mu^3 r}{\varrho T} \cdot \frac{dT}{dx},$$

(1)

where F_t is the thermophoresis force;

  r is the radius of the particle;

μ and ϱ are the viscosity and density of the gas;

  T is the absolute temperature of the gas;

λ_a and λ_i are the thermal conductivities of the gas and the particle;

  dT/dx is the temperature gradient in the gas along the x-axis.

In the case of uniform temperature distribution in an incident flow passing around a surface the temperature of which is different from that of the flow the maximum temperature gradient will occur in the thermal boundary layer [2]. Since the thermophoresis force is directly proportional to the temperature gradient, it follows that the thermophoresis effect will be most strongly pronounced in the boundary layer, where it can have a decisive effect on the nature of the motion of the particle.

In particular, if the temperature of the wall is lower than that of the flow, e.g., in the case of cooled turbine blades, the thermophoresis force will cause the trajectory of motion of the particle to be deflected towards the wall. This may considerably increase the number of particles colliding with the wall or

precipitating on it, in comparison with the case of an uncooled surface, where the temperature of the flow and the wall is the same and the thermophoresis effect is absent.

Since the motion of a particle about a turbine blade depends on various forces, in order to determine the effect of thermophoresis, it is necessary to schematize the phenomena. Let us consider the motion of particles in the laminar boundary layer near a flat wall. This will enable us to ascertain the basic tendencies of the given phenomenon.

In setting up the equations of motion of a particle in the laminar boundary layer, let us assume (Fig. 1) the following:

1. The thermophoresis force is calculated from formula (1), the value of T in this formula being taken equal to the average temperature of the boundary layer

$$T = T_{av} = \frac{T_0 + T_w}{2}.$$ (1')

2. All the physical constants are assumed to be constant for the entire thickness of the boundary layer and are determined for the temperature

$$t_{av} = \frac{t_w + t_0}{2}.$$ (1'')

3. For the temperature distribution in the boundary layer we take the dependence

$$\theta = \theta_0 (2\eta_T - \eta_T)^2.$$ (2)

Here

$$\theta = T - T_w$$ (3)
$$\theta_0 = T_0 - T_w$$ (3')

where T_0, T, and T_w are the absolute temperatures of the flow outside the boundary layer, within the boundary layer, and on the wall, respectively;

η_T is the dimensionless ordinate and

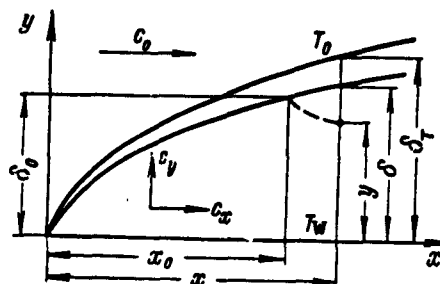$$\eta_T = \frac{y}{\delta_T} \cdot \qquad (4)$$

Fig. 1. Diagram for determining the trajectory in the boundary layer.

The thickness of the thermal boundary layer δ_T, as is known, is related to the thickness of the hydrodynamic boundary layer by the dependence [3]

$$\delta_T = \delta\, Pr^{-\frac{1}{3}}. \qquad (5)$$

Taking $Pr \approx 0.7$ for air, we have

$$\frac{\delta}{\delta_T} = 0.89 . \cdot \qquad (5')$$

The thickness of the hydrodynamic boundary layer is calculated from the formula [4].

$$\delta = 5.83 \; \sqrt{\frac{\nu x}{c_0}} = 5.83 \frac{x}{\sqrt{Re_x}} , \qquad (6)$$

where ν is the kinematic-viscosity factor of the gas.

4. For the distribution of the velocity component c_x we take the approximation

$$c_x = c_0\,(2\eta - \eta^2). \qquad (7)$$

Here

$$\eta = \frac{y}{\delta} ; \qquad (8)$$

c_0 is the flow velocity outside the boundary layer;

η is the dimensionless ordinate of the hydrodynamic boundary layer.

5. For the distribution within the boundary layer of the velocity component c_y perpendicular to the wall we take an approximate dependence obtained by the author by solving the continuity equation with the variation of the gas temperature, and consequently the variation of the density in the boundary layer, taken into account.

This dependence has the form

$$c_y = \frac{c_0}{\sqrt{\mathrm{Re}_x}}\, (a\eta^2 - b\eta^3).$$

$$(9)$$

or

$$c_y = \frac{5.83v}{\delta}\, (a\eta^2 - b\eta^3).$$

$$(9')$$

Let us introduce the dimensionless temperature parameter k

$$k = \frac{T_0}{\theta_n} = \frac{T_0}{T_0 - T_{cT}}.$$

$$(10)$$

The coefficients a and b are functions of this parameter.

Turning to the derivation of the equations of motion of a particle in a nonisothermal boundary layer, let us consider the action of the forces of inertia, the resistance of the medium, and thermophoresis.

Preliminary calculations show that the velocities of the particles relative to the flow are such (small Re numbers) that we can use Stoke's law [5] to express the resistance of the flow to the motion of the particle.

Then, assuming the motion to be planar, we have

$$\left.\begin{array}{l} m\dfrac{dv}{dt} = m\dfrac{d^2y}{dt^2} = F_{ty} - 6\pi\mu r\,(v - c_y); \\[2mm] m\dfrac{du}{dt} = m\dfrac{d^2x}{dt^2} = F_{tx} - 6\pi\mu r\,(u - c_x), \end{array}\right\}$$

$$(11)$$

where v and u are the projections of the velocity of the particle on the y-axis and x-axis, respectively;

F_{ty} and F_{tx} are the projections of the thermophoresis force determined from formula

(1) on the y-axis and the x-axis;

m is the mass of the particle.

From equations (2) and (4) we have

$$\frac{\partial b}{\partial y} = 2b_0 (1 - \eta_\tau) \frac{1}{\delta_\tau} ;$$

(11')

$$\frac{\partial b}{\partial x} = - \frac{b_0 (1 - \eta_\tau) \, \eta}{x \delta_\tau} .$$

(11'')

From formulas (11') and (11'') it can be seen that

$$\frac{\partial b}{\partial x} \ll \frac{\partial b}{\partial y} .$$

(12)

Hence, taking into account formula (1), we obtain

$$F_{tx} \ll F_{ty}.$$

(12')

This enables us to neglect the longitudinal component of the thermophoresis force in equations (11).

Next, let us consider the two cases, where the particles 1) do not have considerable velocities and 2) have a considerable velocity relative to the flow. Of practical interest is the case where the particle velocity is directed towards the wall.

If the particle does not have a considerable velocity relative to the flow and, as a consequence of this, does not undergo important accelerations or retardations resulting from the resistance of the medium, we can neglect the inertial terms, and then equations (11) with (1) and (12') taken into account will assume the following form:

$$\left. \begin{array}{l} - 9\pi \, \frac{\mu^2 r}{\varrho T} \cdot \frac{\lambda_a}{2\lambda_a + \lambda_i} \, b_0 (2 - 2\eta_\tau) \frac{1}{\delta_\tau} - \\ \qquad - 6\pi\mu r \, (v - c_y) = 0; \\ \qquad u - c_x = 0. \end{array} \right\}$$

(13)

After transformations we obtain the system of equations

$$\left. \begin{array}{l} v = \frac{5{,}83^2 v}{\delta} \left[\frac{1}{5{,}83} (a\eta^2 - b\eta^3) - \right. \\ \qquad \left. - \frac{3}{5{,}83^3} \cdot \frac{Q_t}{T} \, \mathrm{Pr}^{2/3} \left(\mathrm{Pr}^{-\frac{1}{3}} - \eta \right) \right]; \\ u = c_0 (2\eta - \eta^2). \end{array} \right\}$$

(14)

Let us introduce the dimensionless coordinates x_1 and y_1

$$x_1 = \frac{x}{x_0};$$

(15)

$$y_1 = \frac{y}{\delta_0},$$

(15')

where x_0 is the coordinate of the entry of the particle into the hydrodynamic boundary layer;

δ_0 is the thickness of the hydrodynamic boundary layer at this spot.

Taking (6) and (8) into account, we have

$$y_1 = \eta \sqrt{x}.$$

(16)

Then, letting

$$\beta = \frac{3}{5.83^2} \cdot \frac{Q_0}{T} \, Pr^{\frac{2}{3}} \, \frac{\lambda_a}{2\lambda_a + \lambda_i}$$

(17)

and bearing in mind that $\frac{dy}{dt} = v$ and $\frac{dx}{dt} = u$, we obtain after a number of transformations and with (16) taken into account

$$x_1 \frac{d\eta}{dx_1} = \frac{\frac{1}{5.83}(a\eta^2 - b\eta^3) - \beta\left(Pr^{-\frac{1}{3}} - \eta\right)}{2\eta - \eta^2} - \frac{\eta}{2}.$$

(18)

This differential equation is solved by assigning values to the coefficients **a** and **b**, which, as was noted above, are functions of the temperature parameter **k**. In particular, solving this equation for Pr = 0.7 and k = 2 with

$$\left.\begin{array}{l} a = 2.329; \\ b = 1.644, \end{array}\right\}$$

(18')

and taking into account the initial conditions

$$x_1 = 1; \quad \eta = 1.$$

(18'')

we obtain a formula relating the coordinates of a particle moving in a boundary layer in the presence of thermophoresis forces

$$\ln x_1 = (1.665 + 0.5\beta) \ln\left[\frac{1.755 + 0.6\beta}{2.755\eta^2 - \eta^3 + 4.587\beta\,(1.1237 - \eta)}\right] +$$

$$+ (0.409 + 1.6\beta) \ln\left|\frac{2.755 - \beta - \eta}{1.755 - \beta}\right| + \frac{1.825 + 0.1\beta}{\sqrt{\frac{1}{\beta} - 0.13}} \times$$

(19)

$$\times \left[\arctan\frac{1 - 0.5\beta}{1.37\sqrt{\beta - 0.13\beta^2}} - \arctan\frac{\eta - 0.5\beta}{1.37\sqrt{\beta - 0.13\beta^2}}\right].$$

Figure 2a shows, in the coordinates x_1 and y_1, the trajectories of a particle for different values of the parameter β with $k = 2$. From the diagram it can be seen that the trajectory of motion of the particle is strongly dependent on the value of β. The greater the value of β, the greater the thermophoresis force and the more rapidly the particle reaches the wall. Thus, under the action of a thermophoresis force, even a particle that does not have a velocity component in the direction of the wall at the initial moment will still strike the wall, assuming, of course, that the wall is sufficiently long.

If the particle, upon entering the boundary layer, has a considerable velocity relative to the laminar boundary layer, resulting, for example, from pulsations and vorticity in the incident flow or from the action of centrifugal forces, we can no longer neglect the inertial terms.

Of practical interest is the case where the velocity of the particle is directed perpendicularly to the wall, for in this case its velocity may be comparable to the velocity component of the flow in the direction of the wall c_y and to the velocity arising as a result of thermophoresis.

In deriving the equations of motion, let us neglect the inertial term along the x-axis and take it into account along the y-axis.

Then equations (11) will assume the form

$$m \frac{dv}{dt} = m \frac{d^2y}{dt^2} = F_{ty} - 6\pi\mu r (v - c_y); \left.\begin{array}{c} \\ \\ \end{array}\right\}$$
$$u - c_x = 0.$$

(20)

Switching over to dimensionless coordinates, after a number of transformations we obtain a system of equations describing the motion of a particle in a laminar nonisothermal boundary layer for $Pr \neq 1$ in the presence of an initial velocity of the particle in the direction of the wall

$$\frac{dv_1}{dl_1} = \frac{5{,}83}{\sqrt{\mathrm{Re}_{x_*}}\,\sqrt{x_1}}\left[\frac{a\left(\frac{y_1}{\sqrt{x_1}}\right)^3 - b\left(\frac{y_1}{\sqrt{x_1}}\right)^3}{5{,}83} - \right.$$

$$\left. - \beta\left(\mathrm{Pr}^{-\frac{1}{3}} - \frac{y_1}{\sqrt{x_1}}\right)\right] - v_1;$$

$$\frac{dx_1}{dl_1} = \frac{c_0\tau}{x_0}\left[2\left(\frac{y_1}{\sqrt{x_1}}\right) - \left(\frac{y_1}{\sqrt{x_1}}\right)^2\right];$$

$$\frac{dy_1}{dl_1} = \frac{c_0\tau}{\delta_0}\,v_1.$$

(21)

where

$$v_1 = \frac{v}{c_0},$$

(22)

$$l_1 = \frac{l}{\tau},$$

(23)

$$\tau = \frac{2}{9}\cdot\frac{\gamma_3 r^2}{\eta g},$$

(24)

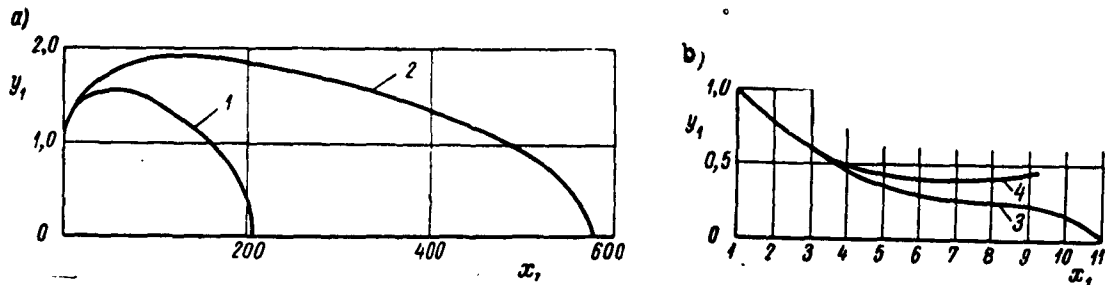Here γ_3 is the specific gravity of the particle.

Fig. 2. The path of the particle in the direction of the wall in the laminar boundary layer: a) without initial velocity; b) with initial velocity: 1) $\beta = 0.02$; 2) $\beta = 0.01$; 3) with thermophoresis forces taken into account; 4) without taking thermophoresis forces into account.

The quantity is called the "relaxation time" and is widely used in aerosol mechanics [1].

The system of equations (21) cannot be solved in the general form and must be solved numerically in each particular case. In order to estimate the nature of the

motion of a particle with a certain initial velocity in the direction of the wall, we used Adam's method [6] to obtain a numerical solution to the system of equations (21) for the following initial conditions:

$$T_0 = 973^0 \text{K} \qquad \beta = 0.02$$
$$k = 2 \qquad Re_{x_0} = 511$$
$$p = 1 \text{ atm abs} \qquad v_1 = -0.06$$
$$c_0 = 20 \text{ m/sec} \qquad \gamma_3 = 2200 \text{ kg/m}^3$$
$$r = 5 \cdot 10^{-6} \text{ m } (d = 10 \, \mu) \qquad \delta_0 = 5.16 \cdot 10^{-4} \text{ m}$$

The particle trajectory calculated from the system of equations (21), which take into account the action of thermophoresis forces, is shown by curve 3 in Fig. 2b. Curve 4 shows the trajectory of the same particle, but without taking into account the action of thermophoresis forces. As can be seen from the diagram, in the first case the particle strikes the wall, while in the second case the particle, having "pierced" as a result of its kinetic energy part of the thickness of the boundary layer, after its velocity in the direction of the wall is attenuated will follow the line of the gas flow and gradually veer away from the wall. This clearly shows that in the case of a particle moving near a cooled wall and possessing an initial velocity in the direction of this wall the phenomenon of thermophoresis also has a decisive effect on the nature of the motion of the particle.

For a given thermal conductivity of the flow λ_a the thermal conductivity λ_i of the particle itself has a strong effect on the nature of the motion of the particle. Obviously, the thermal conductivity of the particle is determined by its chemical and mineralogical composition, and also by its structure, by the presence of pores, cavities, etc. Moreover, the velocity of motion of a particle under the action of thermophoresis is affected by its shape, which is also dependent on its mineralogical composition and structure. Thus, it is clear that particles of different chemical and mineralogical composition and different crystalline

structure will have different trajectories in the boundary layer near the cooled wall and will move and strike the cooled wall in different ways, as a result of which particles with a lower thermal conductivity will approach the wall and precipitate on it faster. This explains the well-known fact [7] that different particles precipitate in different ways on a wall that is colder than the flow. It is known that in this case the particles that precipitate on the wall are primarily particles of definite composition, which may be due to their differing behavior in a temperature field under the action of thermophoresis.

Analyzing the equations of motion of a particle in a laminar nonisothermal boundary layer, it is obvious that the motion of a particle with an initial velocity will be determined by the following dimensionless complexes:

$$\mathrm{Re}_{x_e} = \frac{x_0 c_0}{\nu}; \quad \beta = \frac{3}{5,83^2} \cdot \frac{\theta_0}{T} \cdot \frac{\lambda_u}{2\lambda_u \div \lambda_r} \mathrm{Pr}^{\frac{2}{3}};$$

$$\frac{\tau c_0}{\delta_0}; \quad v_1 \cdots \frac{v_0}{c_0}; \quad k = \frac{T_0}{\theta_0}.$$

Note that the quantity $c_0 \tau$ is called the "inertial path" of a particle with an initial velocity c_0 [1]: it is equal to the path traversed by a particle with an initial velocity c_0 in a medium devoid of external forces. Thus the complex $\frac{\tau c_0}{\delta_0}$ characterizes the "piercing power" of the particle with reference to the thickness of the boundary layer.

Special mention should be made of the complex β and the temperature parameter k, which in the case $v_1 = 0$ completely determine the motion of the particle in the dimensionless coordinates x_1, y_1. In this case they are the criteria determining the nature of the motion of the particle. The temperature parameter k characterizes the intensity of the cooling of the wall, while β characterizes the ratio between the thermophoresis forces and the hydrodynamic forces.

For the purpose of making a qualitative experimental check of the above-mentioned assumptions concerning the important influence of the thermophoresis effect on the process of precipitation of particles on a cooled wall we carried

out special experiments with plates, on the surfaces of which different temperatures were maintained and which were placed in a hot gas flow (t = 610^0C) containing fine particles of ash.

Three pairs of plates were set up in the flow: 1) cooled with a wall temperature of 90^0C; 2) not cooled with a wall temperature of 607^0; 3) heated with a wall temperature of 680^0.

Experiments with a cooled and an uncooled plate showed that the cooled plate wears out many times faster than the uncooled plate. As a result of an experiment with a heated and an unheated plate it was ascertained that precipitation was almost entirely absent on the heated plate. Small depositions occurred only at the sites of roughnesses and aerodynamic shadow. Obviously, in this case the conditions of precipitation of ash particles on the plate surfaces were identical in every respect, except the direction of the heat flux. Thus the great difference in the amount of precipitation is due to the fact that in the case of the heated plate the thermophoresis forces were directed away from the plate and prevented ash particles from precipitating on the surface. The small depositions that occurred in the zone of aerodynamic shadow and breakaway may be due to the fact that particles landing in the vortices of the flow received therefrom a velocity in the direction of the wall greater than the velocity received from the thermophoresis force counteracting this motion.

Obviously, in the experiment with the cooled plate the considerable depositions on it are the consequence of the thermophoresis forces acting on the particles. These forces are directed toward the wall and further the increase of depositions. Thus the experiments carried out corroborate the theory stated above concerning the important influence of the thermophoresis effect on the process of precipitation of aerosol particles on cooled or heated walls.

On the basis of the aforesaid we can draw the following conclusions:

1. In the formation of depositions on cooled surfaces the action of

thermophoresis is basic in comparison with other factors affecting the process of precipitation. This is of particularly great importance in the case of high-temperature cooled turbines operating on combustion products containing volatile ash. In the case of gas turbines with a uniform temperature distribution in the incident flow the thermophoresis effect will manifest itself mainly in the boundary-layer region, where the maximum temperature gradient occurs.

2. A particle impinging on a nonisothermal boundary layer near the cooled wall, under the action of thermophoresis forces, will necessarily strike the wall, provided that the wall is sufficiently long.

3. The nature of the motion of a particle in a nonisothermal boundary layer is influenced decisively by both the temperature parameter $k = \dfrac{T_0}{\theta_0} = \dfrac{T_0}{T_0 - T_W}$, and by the ratio between the thermal conductivities of the particle and the medium λ_1 / λ_a.

4. By choosing the system of coordinates $x_1 = \dfrac{x}{x_0}$ and $y_1 = \dfrac{y}{\delta_0}$ in the case of absence of an initial velocity of the particle relative to the flow, the nature of the motion of the particle in a laminar boundary layer will depend only on the temperature parameter $k = \dfrac{T_0}{\theta_0}$ and the dimensionless quantity

$$\beta = \frac{3}{5,83^2} \cdot \frac{\theta_0}{T} \, Pr^{\frac{2}{3}} \frac{\lambda_a}{2\lambda_a + \lambda_l} \, .$$

5. In the case of greatest practical interest, where the particle has an initial velocity in the direction of the wall, the motion of the particle in the coordinates x_1, y_1 will be determined by the complexes

$$Re_{x_0} = \frac{x_0 c_0}{\nu} \, ; \quad \beta = \frac{3}{5,83^2} \cdot \frac{\theta_0}{T} \, Pr^{\frac{2}{3}} \frac{\lambda_a}{2\lambda_a + \lambda_l} \, ; \quad v_1 = \frac{v_0}{c_0} \, ;$$

$$k = \frac{T_0}{\theta_0} \, ; \quad \frac{\tau c_0}{\delta_0} \, .$$

6. Calculations made on the basis of the above theory show that particles with different chemical and mineralogical compositions and different thermal conductivities and shapes, when in a field with a temperature gradient, must move along different trajectories with the particles of lower thermal conductivity striking the wall sooner. This explains the well-known phenomenon, where deposition of different ash components on cooled surfaces occurs dissimilarly

and "selective deposition" takes place.

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